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ELECTRICAL CONDUCTIVITY OF INSULATOR SURFACE ICES

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ABSTRACT

The electrical conductivity of ice fragments removed from artificially contaminated and iced insulators was measured in the laboratory. Icicle-tips and other bottom surface pieces that freeze last were frequently found to have conductivities two to three times greater than the upper portions of ice that freeze first. An explanation of this phenomenon was found in crystallization theory, but its importance in the flashover process of contaminated and iced insulators has not been established. Therefore, for the time being, when making artificial rain with demineralized water, the conductivity should be closely matched to natural rain.

INTRODUCTION

Hot and cold fog testing of artificially contaminated and iced insulators requires careful attention to the conductivity of the water supply. Ordinary tap water has a conductivity and ion concentration that differ from natural rain or fog. Tap water must be conditioned prior to its use. The situation is even more complicated during freezing in that the conductivity of the water can change significantly if the ice forms slowly. Investigations have shown that even the conductivity of the surface ice can vary, especially between that on the upper surface and the icicles that form on the lip. These observations led to a series of investigative experiments which include a study of ice conductivities at temperatures below freezing and a study of the conductivity of the melt water. This report deals mainly with these physical characteristics and makes no attempt to explain the behaviour of iced and contaminated insulators from the measured data.

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CONDUCTIVITY OF ICE

One of the first experiments* was to measure the electrical conductivity of ice over a reasonable temperature range at some fixed current density. For simplicity, real insulators were not used. Instead, a special coaxially-shaped conductivity cell was constructed so that its internal dimensions would not be mechanically distorted by the expansion of freezing ice. This design also avoided any error-causing parallel-current paths through thin layers of surface water that could form from condensation. A sketch of the conductivity cell is shown in Figure 1; its conductivity is derived in Appendix 1.

The cell was totally immersed in water and allowed to freeze slowly in a cabinet of dry ice. A clear dense ice was obtained by boiling the water to drive off dissolved gases. All conductivity measurements were made with 60 Hz ac to minimize polarization effects. The results are plotted in Figure 2.

Measurement Results

Figure 2 shows a plot of electrical conductivity versus temperature for ice made from ordinary tap water (346 μS/cm at 25°C) and for ice made from deionized water (3 μS/cm at 25°C). The graph shows that the conductivity of the deionized-water ice is relatively independent of temperature until the temperature approaches zero degrees. The tap-water ice, however, shows a ten times increase over the same temperature range.

It is interesting to compare the conductivity of the above homogeneous ices (Figure 2) with the conductivity of rime ices (Figure 3, - reproduced from Reference 1). The conductivity of the rime ices increases more rapidly with temperature than does the solid ices. This is surprising, especially because it also occurs for rime ice made from distilled water. Rime ice has a large surface area. This could explain the results if its fibrous structure is assumed to have a thin layer of surface water. Dryness is important; early experiments with solid ice, for example, showed a similar behaviour until precautions were taken to avoid the effects of moisture layers on the ice surface.

Wet ice provides two parallel current paths and, therefore, can be considered to have both volume and surface conductivities.

Current Density Effects

All the above measurements were made at a fixed current level. Some additional conductivity measurements were made at other current levels to check for nonlinear effects. This was done by measuring the conductivity quickly using a pulsed current. The restricted power dissipation limited the temperature rise. The results showed no significant difference; the conductivity of the ice appears to have no dependency on the current density over the range of currents used.

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* All work reported here was completed in November 1987.

THE CONDUCTIVITY OF WATER VERSUS TEMPERATURE

The conductivity of water as a function of temperature is easily measured in the laboratory. This measurement was done on tap and deionized water as a routine check to see if there was anything unusual about the water being used to make ice. Figures 4 and 5 show the conductivities of deionized water and tap water respectively; both appear to be linear functions of temperature but each has a different slope. There is nothing new or surprising about these results.

Additional measurements were made over a range of current levels, at constant temperature, to check for nonlinear effects. The measurements were made quickly using pulsed dc and spaced out over time to avoid electrode gassing and heating of the water. The results, shown in Figures 6 and 7, show that the conductivity of tap water and deionized water have no significant dependency on current density over the range of currents used.

CONDUCTIVITY OF INSULATOR ICE AND ICICLES

During tests on artificially contaminated and iced insulators, shards of ice frequently fall off the insulator surfaces as the temperature rises. Conductivity measurements of these pieces showed that the icicles were significantly more conducting than the surface ice. Leaching of the surface contamination was initially suspected until it was noticed that the upper surface ice had less conductivity than the rain water. It was soon discovered that clean insulators gave similar results. Here are some typical results from Test #7 of September 23, 1987 involving cap and pin insulators with a contamination ESDD level of 0.018 mg/cm^2:

1) test rain (tap water) 325 µS/cm
2) cap ice 227 µS/cm
3) icicles 633 µS/cm

Another example from Test #113 (October 1, 1987) involved one clean insulator and one contaminated unit having an ESDD level of 0.027 mg/cm^2:

From the clean unit:

1) test rain (tap water) 320 µS/cm
2) cap ice 305 µS/cm
3) icicles 1063 µS/cm

From the contaminated unit:

1) test rain (tap water) 320 µS/cm
2) cap ice 344 µS/cm
3) icicles 1086 µS/cm

CONTROLLED ICE MAKING EXPERIMENTS

Several different methods of making ice were tried in the laboratory in an effort to duplicate the samples of varying conductivity that were obtained from insulator testing. Ice was made, for example, with and without an applied voltage and by spraying water onto a cooled substrate to simulate an insulator surface. No method resulted in ice with a significant variability in conductivity. The following simple experiment finally produced results: a beaker of water was allowed to freeze slowly and quietly from the top down until only a little water remained at the bottom. The following conductivities were measured:

1)	original tap water	315 μS/cm
2)	ice (top surface)	237 μS/cm
3)	ice (bottom surface)	248 μS/cm
4)	remaining unfrozen water	622 μS/cm
5)	remix of 2,3,4 above	314 μS/cm

These results can be explained simply as an example of purification by crystallization. Recrystallization is a well known technique in the chemical and food-processing industries and has many variations. High temperature crystallization, for example, is commonly used to purify semiconductors in a process called Zone Refining. Physically, the formation of ice crystals at the liquid-solid interface prefers to exclude foreign none-water molecules because the potential energy of the crystal lattice varies inversely with the number of dislocations. (Dislocations are introduced by foreign molecules in a lattice of pure ice.) Physical processes tend to move in a direction of minimum potential energy.

CHEMICAL ANALYSIS OF WATER

It is frequently asked if the deionized water used to make rain and fog in the insulator test chamber is chemically different from real rain water. To answer this question a sample of rain water was collected on November 17, 1987 at 9:30 AM, from the roof of the laboratory building. This sample, plus one each of deionized and ordinary tap water, were analyzed by the chemical department. The results are shown in Table 1.

Table 1
Water Analysis

	Tap Water	Deionized Tap Water	Rain Water
pH	8	7	6.4
conductivity μS/cm	300	55	24.1
sulphate	29.5	4.92	10.3
nitrate	*	*	2.58
fluoride	1.1	0.21	0.09
chloride	24.3	2.81	2.71
calcium	40	6.4	4
magnesium	8.4	1.4	0.6
potassium	1.5	0.24	0.37
sodium	12	2.0	1.7

* insufficient quantity for analysis.
All quantities are in ppm except pH and conductivity.

Except for sulphate, these data show that this particular sample of rain water is similar to the deionized tap water. The chemical nature of rain, however, can be highly variable both in time and place and so the data cannot be generalized; see, for example, Table 2. The effectiveness of the deionizing process in removing contaminates is also noteworthy.

CONCLUSIONS

1) The conductivity of ice made from deionized water is roughly constant (0.007 μS/cm) between -20 and -0.1°C.

2) The conductivity of tap-water ice is not constant but increases about ten times from a starting value of 0.15 (μS/cm) between -20 and -0.1°C.

3) Tap-water ice is 20 to 100 times more conductive than deionized-water ice between -20 and -0.1°C, respectively.

4) The conductivity of tap and deionized water is a linear function of temperature.

5) The conductivity of tap and deionized water show no dependence on current density for a fixed temperature.

6) Deionized tap water can be similar to rain water in some cases but not as a general rule because rain water is highly variable.

7) A wet freezing rain is more likely to build insulator ice that varies in conductivity than is a quick freezing ice.

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TABLE 2 (Taken From Reference 2)

CHEMICAL COMPOSITION OF PRECIPITATION SAMPLES

MONTH 1980	DAY	(1) SAMPLE COLLECTED	(2) SAMPLING SITE	PRECIPITATION AMOUNT MM	TYPE	PH	PRECIPITATION ANALYSIS $SO_4^=$	NO_3^-	CL^- MG/L	NH_4^+	CA^{++}	MG^{++}	NA^+	K^+
SEPTEMBER	1	M	E	23.1	RAIN	3.54	5.20	4.10	.23	.85	.27	.18	.15	0.17
	1	M	M	15.7	RAIN	3.65	4.30	3.71	.13	1.22	.37	.26	.12	0.11
	1	M	TN	4.1	RAIN	3.70	4.10	3.00	.42	.34	.62	.11	.11	0.12
	1	M	V	17.3	RAIN	3.40	7.00	3.05	.18	1.02	.66	.07	.06	0.03
	2	TU	E	3.7	RAIN	3.60	6.30	2.80	.05	1.31	.41	.08	.03	0.09
	2	TU	M	8.9	RAIN	3.50	3.80	2.90	.07	.68	.41	.08	.04	0.03
	2	TU	TN	2.7	RAIN	3.80	2.35	2.60	.48	.19	.62	.11	.07	0.08
	2	TU	V	8.1	RAIN	3.70	3.10	2.00	.06	.46	.25	.18	.07	0.07
	7	SU	F	6.1	RAIN	4.10	4.30	2.60	.07	.50	.45	.11	.04	0.02
	8	M	A	9.6	RAIN	3.85	1.90	1.30	.50	.31	.12	.02	.06	0.05
	9	TU	E	7.5	RAIN	4.65	5.50	3.80	.21	.72	.36	.07	.14	0.06
	9	TU	M	10.0	RAIN	4.10	4.30	2.10	.11	.97	.63	.09	.15	0.05
	9	TU	TN	5.7	RAIN	4.60	6.10	4.30	.18	1.18	.41	.17	.07	0.06
	9	TU	V	12.3	RAIN	4.80	4.40	2.80	.27	.53	4.60	.13	.09	0.18
	9	TU	MI	11.6	RAIN	3.60	1.90	1.20	.50	.29	.14	.02	.05	0.03
	12	F	E	3.7	RAIN	4.05	4.30	2.30	.17	.63	.41	.06	.23	0.13
	13	SA	E	12.7	RAIN	3.90	7.60	5.35	.25	1.10	.78	.15	.20	0.02
	13	SA	TN	1.9	RAIN	3.95	5.45	2.85	.70	.58	.26	.81	.10	0.12
	14	SU	E	9.5	RAIN	4.45	5.70	3.10	.18	.71	.37	.08	.21	0.06
	14	SU	M	19.3	RAIN	4.20	5.40	2.28	.24	1.54	.12	.05	.11	0.22
	14	SU	TN	9.4	RAIN	3.90	6.70	2.75	.24	.43	.27	.07	.03	0.05
	14	SU	V	13.6	RAIN	3.10	7.40	3.50	.22	.78	1.49	.10	.05	0.11
	14	SU	MI	9.5	RAIN	2.90	4.00	1.76	.17	.32	.11	.02	.02	0.02
	16	TU	A	13.7	RAIN	3.55	3.10	2.80	.31	.61	.17	.08	.17	0.04
	16	TU	MI	19.2	RAIN	3.00	3.08	1.29	.14	.43	.08	.02	.04	0.03
	17	W	E	4.2	RAIN	5.15	3.70	1.80	.17	1.07	1.12	.43	.10	0.17
	17	W	TN	3.0	RAIN	5.20	5.40	2.50	.43	.72	1.73	.54	.10	0.24
	18	TH	MI	6.4	RAIN	3.00	4.82	3.04	.27	.38	.07	.02	.06	0.02
	21	SU	V	7.0	RAIN	3.30	10.50	4.70	.65	1.46	5.25	.28	.29	0.54
	21	SU	MI	7.0	RAIN	3.70	8.50	4.60	.24	1.44	.58	.08	.07	0.06
	22	M	E	19.6	RAIN	4.85	5.10	3.30	.09	.91	.84	.23	.07	0.06
	22	M	TN	14.7	RAIN	4.60	3.60	1.65	.26	.22	.49	.43	.10	0.51
	22	M	V	11.7	RAIN	3.30	2.50	1.50	.24	.45	.33	.03	.13	0.12
	25	TH	M	5.5	RAIN	4.80	4.70	3.90	.15	1.20	.71	.31	.17	0.11
	25	TH	TN	5.7	RAIN	5.60	6.70	9.60	.70	.97	2.86	1.10	.72	0.23
	25	TH	MI	8.5	RAIN	4.00	4.10	4.60	.20	.75	.37	.07	.04	0.06
	26	F	M	17.5	RAIN	4.40	2.32	2.10	.32	.46	.29	.05	.20	0.17
	26	F	V	17.8	RAIN	4.10	2.92	3.35	.20	.42	.50	.05	.07	0.09
	28	SU	A	8.7	RAIN	4.55	3.70	3.60	.20	.91	.22	.07	.04	0.03
	29	M	A	6.2	RAIN	4.25	4.90	2.10	.15	1.10	.31	.04	.03	0.02
	30	TU	MI	7.2	RAIN	4.00	5.40	2.60	.15	1.39	.26	.05	.05	0.06

(2) P-PEACOCK PT , B-BURLINGTON , TN-TORNTO(427+5) , E-ESSEX , MI-MISSISSAGI , M-MUSKOKA , A-ABITIBI CANYON , V-VANKLEEK HILL

REFERENCES

1) Khalifa, M.M. and Morris, R.M., "Performance of Line Insulators Under Rime Ice", IEEE Trans. on Power Apparatus and Systems PAS-86 No 6 June 1967, pp 692-698.

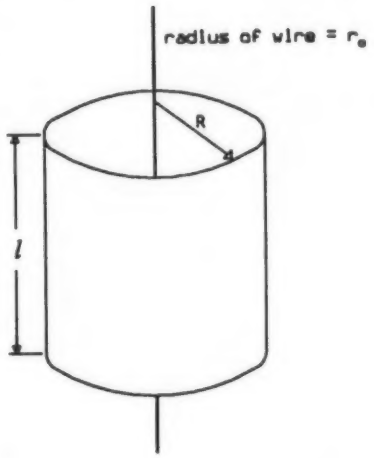
2) Handy, B., "Ontario Hydro's Air And Precipitation Monitoring Network-Data Report For September-December, 1980", Ontario Hydro Research Report No C81-113-K.

APPENDIX

ANALYSIS OF RESISTIVITY CELL USED TO MEASURE THE CONDUCTIVITY OF ICE

Construction

A coaxial resistivity cell was made from an aluminum tube and stainless steel wire as shown below (see also Figure 1).



l = 16.4 cm
$2r_o$ = 0.16 cm
R = 1.75 cm

The stainless steel wire extending beyond the tube ends was insulated with teflon tubing. The assembly was totally immersed in water before freezing.

Analysis

For any current I flowing into the central wire, the radial current density J established inside the tube is given by:

$$J = \frac{I}{2\pi r l} \quad \text{amperes / cm}^2 \qquad (1)$$

The current density J is related to the internal electric field E and medium resistivity ρ by the well known general form of Ohm's Law:

$$J = \frac{E}{\rho} \quad \text{amperes / cm}^2 \tag{2}$$

By substituting equation (1) into equation (2) the electric field E can be integrated over the internal spacing ($R-r_o$) to yield the voltage V applied between the tube and central wire.

$$V = \int_{r_o}^{R} E \, dr$$

$$= \frac{\rho I}{2\pi l} \int_{r_o}^{R} \frac{dr}{r} \quad \text{volts}$$

The integration gives:

$$V = \frac{\rho I}{2\pi l} \ln \left| \frac{R}{r_o} \right| \quad \text{volts} \tag{3}$$

Dividing by I gives the resistance R_t between the tube and central wire.

$$R_t = \frac{V}{I} = \frac{\rho}{2\pi l} \ln \left| \frac{R}{r_o} \right| \quad \text{ohms} \tag{4}$$

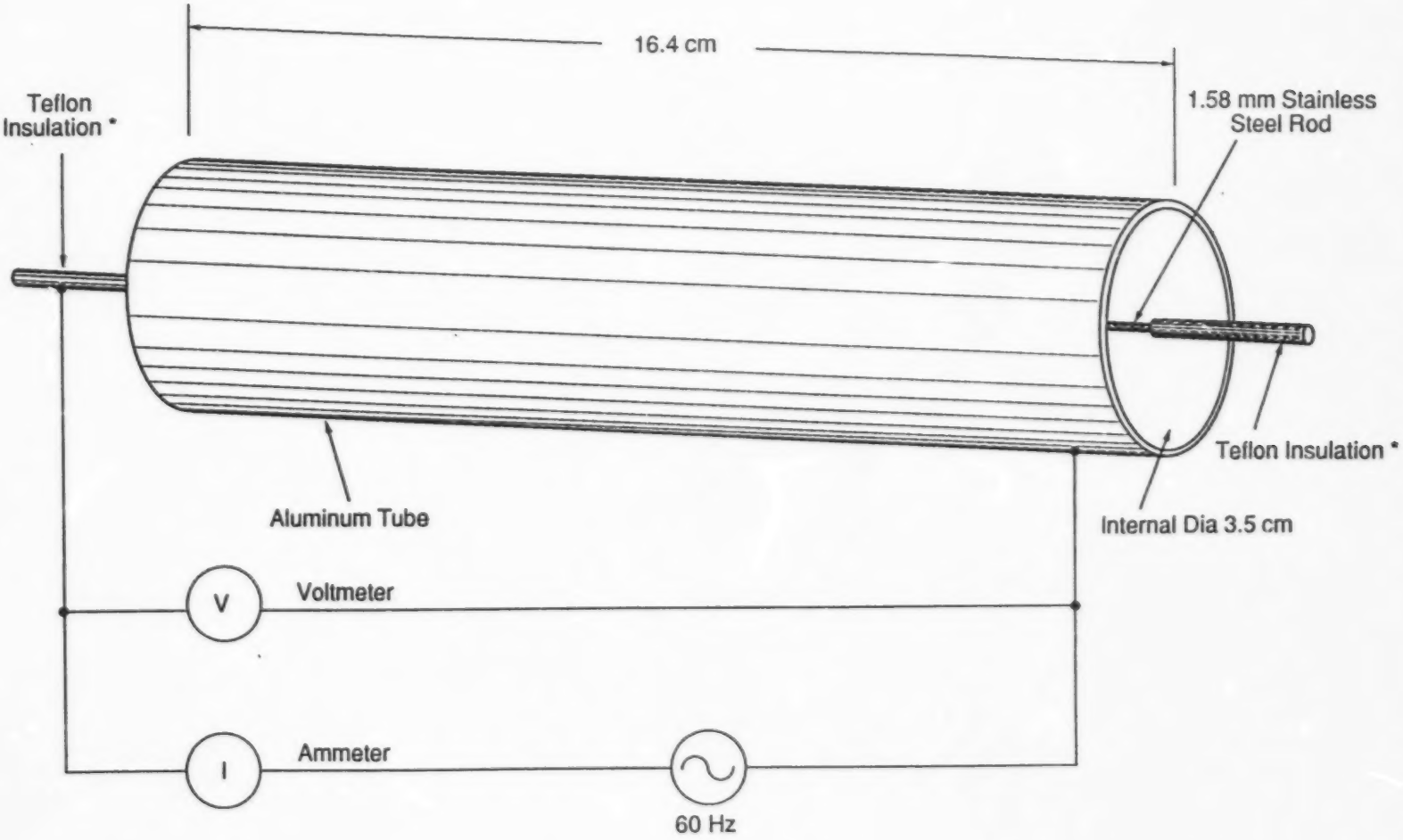
Equation (4) can now be solved for the resistivity ρ or conductivity ($\sigma = \frac{1}{\rho}$) of the internal medium.

$$\sigma = \frac{I}{V} \cdot \frac{1}{2\pi l} \ln \left| \frac{R}{r_o} \right| \quad \text{Siemens / cm}$$

Substituting values for l, R and r_o gives:

$$\sigma = 0.03 \frac{I}{V} \quad \text{Siemens / cm} \tag{5}$$

Equation (5) was used to calculate the data plotted in Figures 2, 4 and 5.



Ice Conductivity = 0.03 $\frac{I}{V}$ Siemens/cm

* Only the rod section projecting beyond the tube-end was insulated

FIGURE 1

COAXIAL CELL USED TO STUDY THE CONDUCTIVITY OF ICE

89-31

Ja 9 DISK
178187-RD

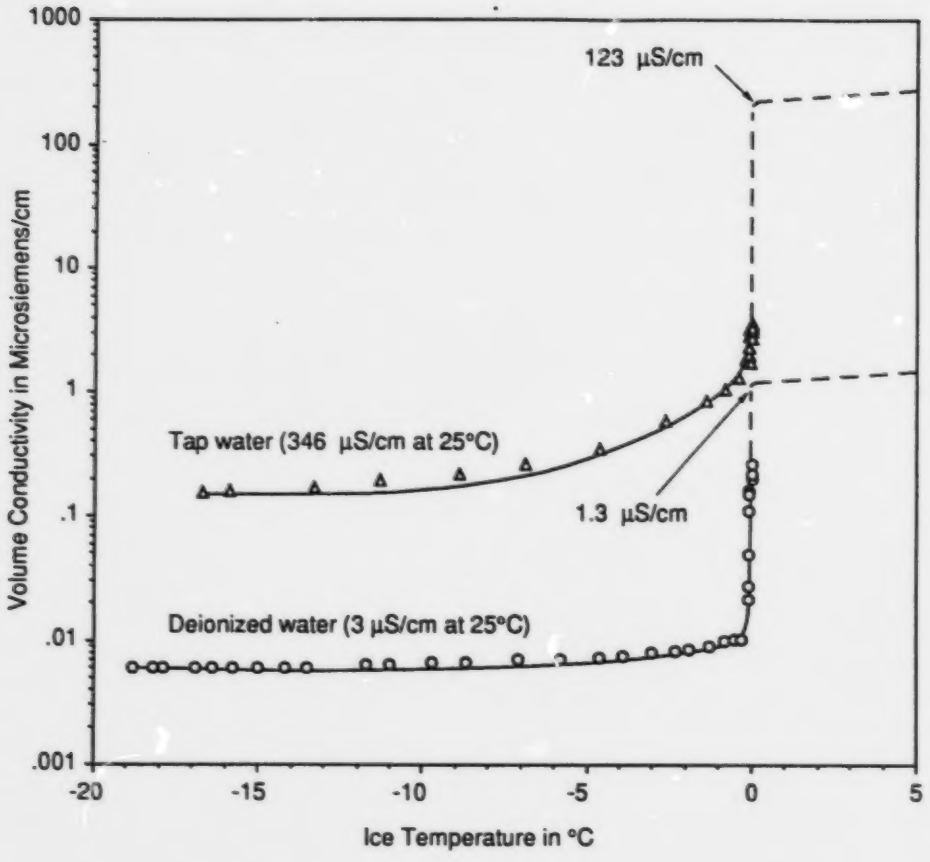


FIGURE 2

60 Hz CONDUCTIVITY OF ICE VS TEMPERATURE

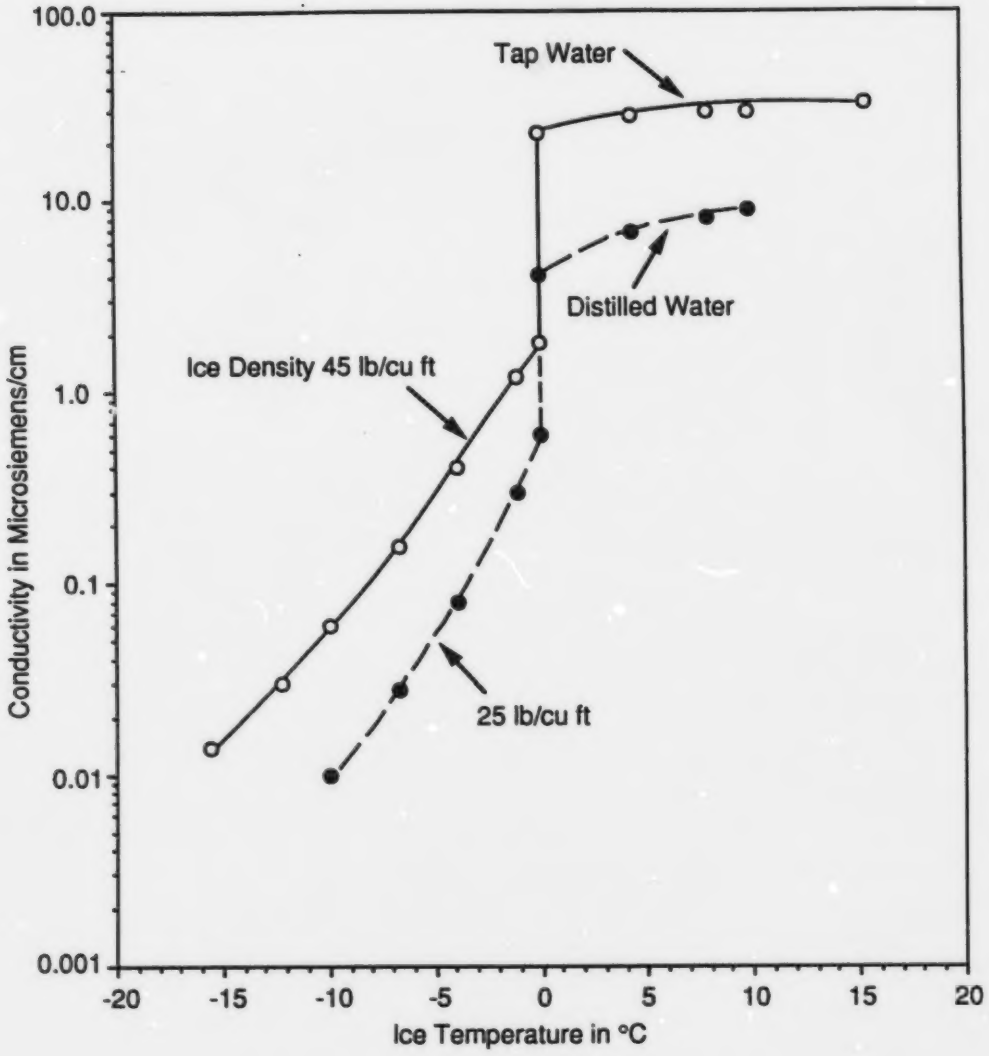


FIGURE 3

CONDUCTIVITY OF RIME ICE VS TEMPERATURE
(TAKEN FROM REFERENCE 1)

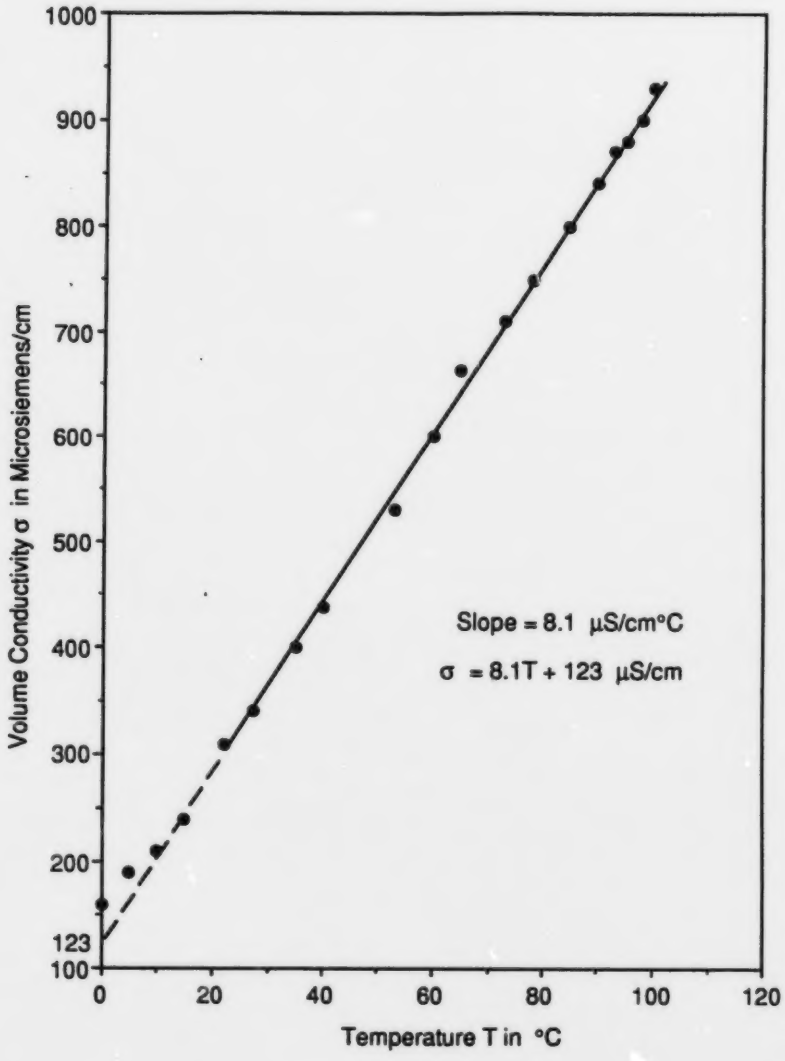


FIGURE 4

CONDUCTIVITY VS TEMPERATURE FOR TAP WATER

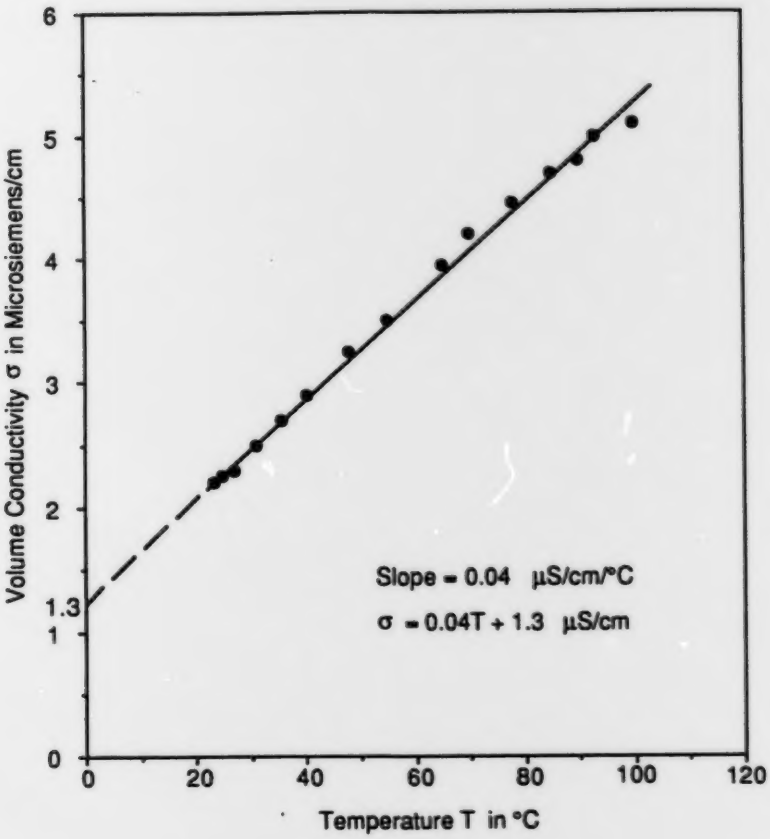


FIGURE 5

CONDUCTIVITY VS TEMPERATURE FOR DEIONIZED WATER

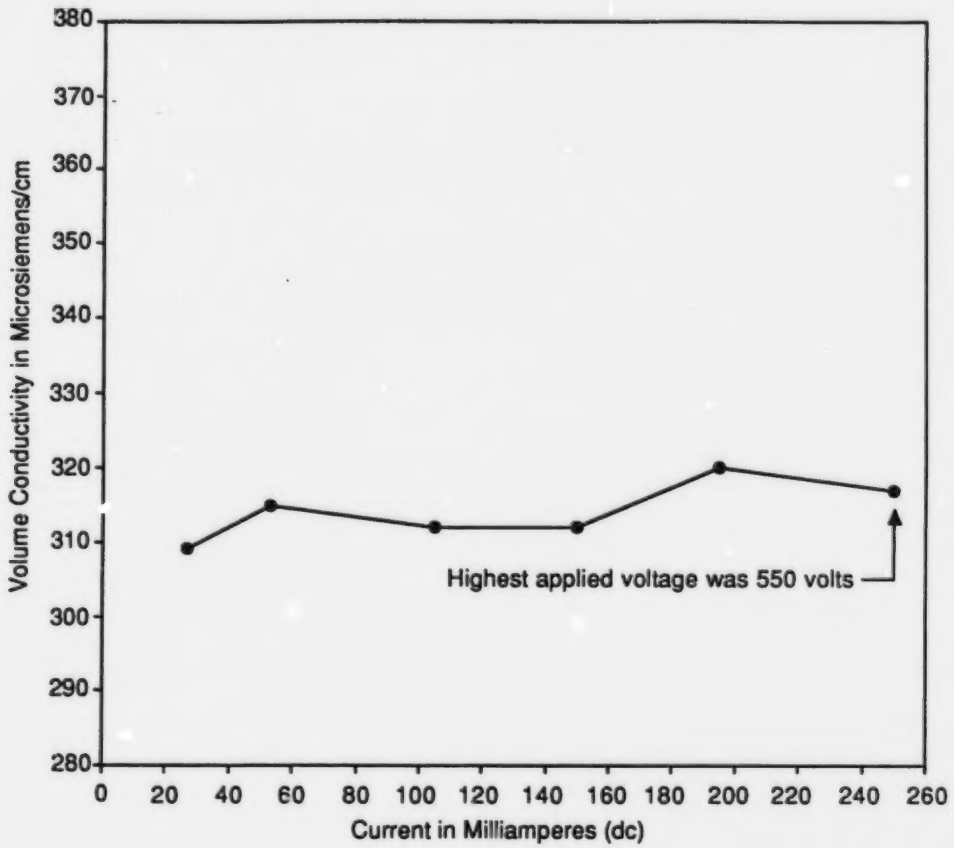


FIGURE 6

CONDUCTIVITY VS CURRENT FOR TAP WATER AT 23°C

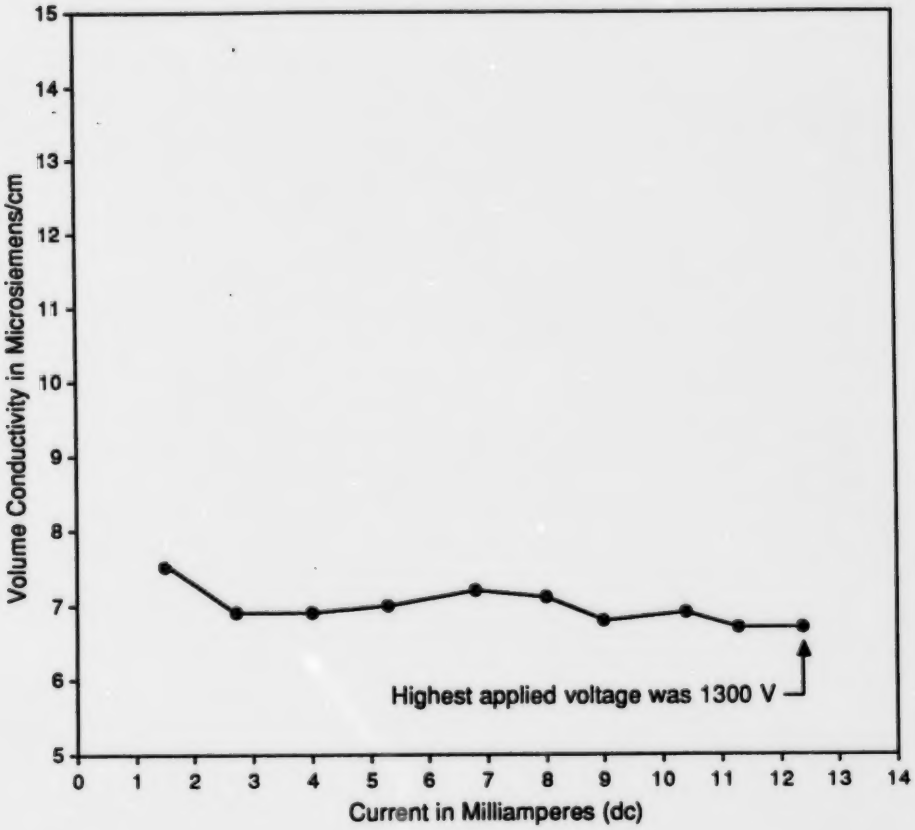


FIGURE 7

CONDUCTIVITY VS CURRENT FOR DEIONIZED WATER AT 23°C